

Evaluation of Range, Bandwidth, and Energy Efficiency for Integrated Sensing and Communication of UAV Based on DroneKit and NS-3

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Abstract—This study analyzes the performance of a UAV-based environmental monitoring system that integrates Integrated Sensing and Communication (ISAC) with 5G simulation. The framework uses DroneKit to generate flight trajectories and NS-3 to simulate network behavior, enabling evaluation of how communication performance changes with distance and bandwidth. The results indicate that as the distance between the UAV and the base station increases from 50 meters to 500 meters, latency rises from 11 milliseconds to 48 milliseconds, throughput decreases from 18 Mbps to 3 Mbps, and the packet delivery ratio drops from 99% to around 85–87%. The simulation results confirm the feasibility of integrating UAV-ISAC for real-time environmental sensing, thereby supporting the study's findings. Additionally, the results highlight essential trade-offs between distance, bandwidth, and energy efficiency. The proposed framework offers practical insights for optimizing multi-UAV coordination, enhancing communication reliability, and effective resource allocation in next-generation environmental monitoring systems.

Keywords— UAV, Environmental Monitoring, Integrated Sensing and Communication (ISAC), Simulation.

I. INTRODUCTION

In recent years, environmental pollution and climate change have intensified the demand for real-time and mobile monitoring. Fixed stations provide stable data but are limited in coverage, deployment flexibility, and responsiveness to sudden air-quality incidents or extreme weather. By contrast, Unmanned Aerial Vehicles (UAVs) offer high mobility and flexible deployment, enabling rapid adjustment of monitoring areas and serving as an important complement to fixed infrastructure [8].

With advances in wireless technologies, Integrated Sensing and Communication (ISAC) has attracted growing attention. The core idea of ISAC is to use a single signal/waveform to carry both sensing and communication functions [6]. However, because sensing and communications share limited spectrum resources, performance trade-offs inevitably arise; studies

report that under high interference, communication quality may degrade due to resource allocation [4], [5].

Motivated by these challenges, we propose a UAV-based ISAC simulation framework. We employ DroneKit/Gazebo to generate UAV flight trajectories and use NS-3 to simulate 5G communication performance, combined with synthetic sensing data (e.g., PM2.5 or thermal imagery) for analysis. Our goal is to validate the feasibility and identify the challenges of applying UAV-ISAC to environmental monitoring, and to outline future extensions in multi-UAV cooperation and resource allocation.

II. RELATED WORK

A. ISAC Foundations

ISAC has emerged as an important research direction in wireless communications and a promising 6G candidate, enabling a unified waveform for both sensing and communications [6]. Since sensing and communications must share limited spectrum, resource-allocation trade-offs are unavoidable; without careful design, increased latency or reduced sensing accuracy may occur [4], [5].

B. UAV Communications in 5G and Beyond

Prior works have surveyed UAV applications and challenges in 5G/6G, including coverage, relaying, trajectory design, interference management, and energy constraints [3], [7], [2]. These studies highlight UAVs as key elements in future wireless networks.

C. Environmental Monitoring with UAVs

UAVs are widely used for environmental monitoring. AdaptNet demonstrates the potential of integrating sensing and communication in UAV networks with flexible resource allocation [1], while surveys show UAVs can effectively complement fixed stations for PM2.5 and other environmental metrics [8]. Despite progress, simulation studies that jointly

consider ISAC and UAV-based environmental monitoring remain limited, motivating our UAV-ISAC framework.

III. METHODOLOGY

This study proposes a UAV-based ISAC simulation framework. The overall process encompasses three main components: UAV flight trajectory simulation, 5G communication performance simulation, and sensing data simulation, followed by a comprehensive performance index analysis, as shown in Fig. 1.

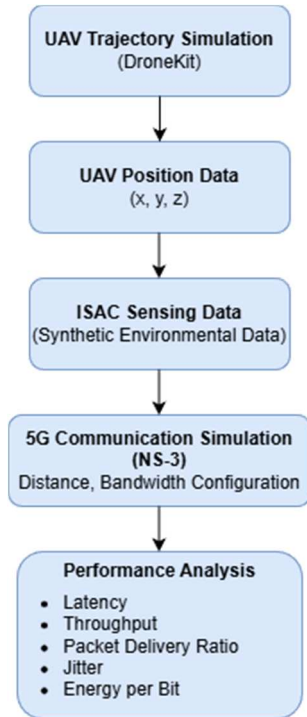


Figure 1. UAV-ISAC Simulation Architecture Flowchart

A. UAV Flight Trajectory Simulation

This study utilizes DroneKit to establish the UAV flight trajectory, simulating the drone's movement across different altitudes and paths and generating the corresponding coordinate data. Although the current work focuses on a simplified 2D rectangular trajectory, DroneKit's integration is essential because it provides a standardized and dynamic interface for Realistic Simulation, laying the foundation for incorporating complex, dynamic maneuvers and 3D flight paths (as initially intended with Gazebo). Furthermore, the framework ensures Future Extensibility by directly supporting the planned future work on complex multi-UAV cooperation scenarios and dynamic resource allocation. While the 2D data is sufficient for current communication analysis, the simulation architecture guarantees scalability for real-world complexity.

B. 5G Communication Simulation

For the communication simulation, the NS-3 platform is utilized to establish the 5G network environment, where the UAV is designated as a mobile node and the base station as a fixed node. The impact on communication performance is

tested by varying the distance between the UAV and the base station. The primary metrics measured in this paper are latency, throughput, and bandwidth sensitivity, which are used to simulate the communication behavior of the UAV-ISAC system under different scenarios. In all rectangular trajectory simulations, the UAV maintains a fixed altitude (Z) of 100 meters relative to the base station and ground node. This fixed altitude is critical for establishing the initial path loss calculation in the 5G distance measurements.

IV. RESULTS

UAV Rectangular Flight Trajectory (Fig. 2) The simulation establishes a rectangular trajectory using DroneKit to model the UAV patrolling a monitoring area. The base station (BS) is placed at a fixed, central location. As depicted in Fig. 2, the UAV departs from a starting point and flies clockwise along the rectangular path. Arrows clearly indicate the cruising direction along each segment. This design ensures dynamic distance changes between the UAV and the BS at different positions, thereby reflecting the differences in communication performance. The distance from the UAV to the fixed BS continuously changes, ranging from a minimum distance (e.g., 50 m) to a maximum distance (e.g., 500 m), which simulates the state of the UAV continuously patrolling in an actual mission and provides a distance benchmark for subsequent performance analysis.

Latency and throughput are the most fundamental and critical performance indicators of a communication system. Latency determines whether sensing data can be returned in real-time, while throughput limits the type and quality of transmittable data, such as high-frequency PM2.5 data or real-time video streaming. In the simulation results of this study, distance has a significant impact on both metrics.

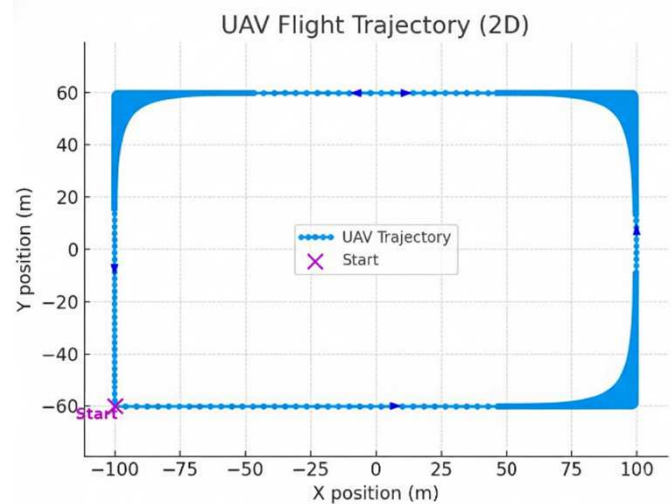


Figure 2. UAV Rectangular Flight Trajectory

As shown in Fig. 3, when the distance between the UAV and the base station increases from 50 m to 500 m, the average latency rises from approximately 11 ms to about 48 ms, and the throughput decreases from around 18 Mbps to only about 3

Mbps. This trend is consistent with the Friis path loss theory, indicating that increased distance leads to a degradation of signal quality and a deterioration of transmission efficiency. For UAV environmental monitoring, if high-resolution sensing data needs to be transmitted over long distances, the communication real-time capability and reliability will be significantly challenged.

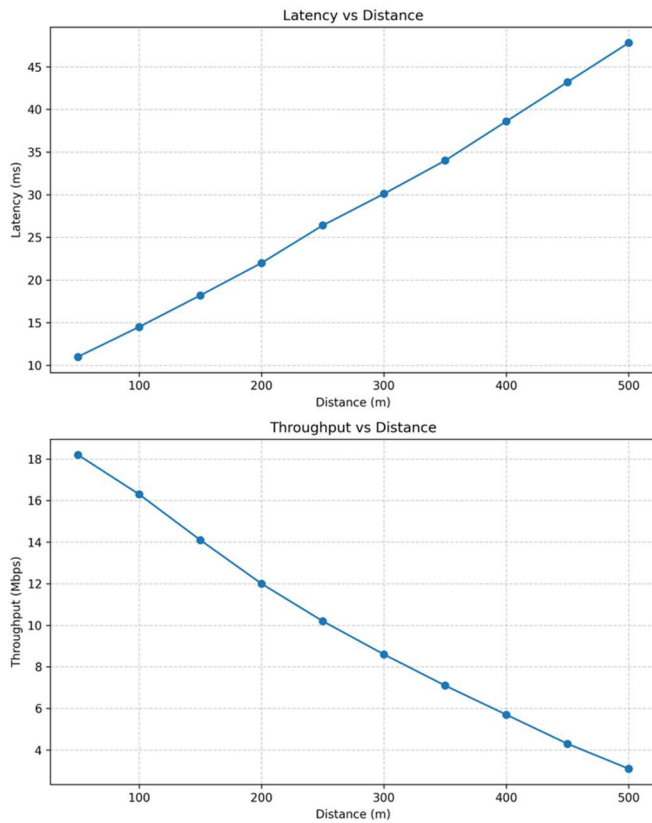


Figure 3. Latency and Throughput Changes with Distance

In addition to latency and throughput, Packet Delivery Ratio (PDR) and jitter also reflect communication quality.

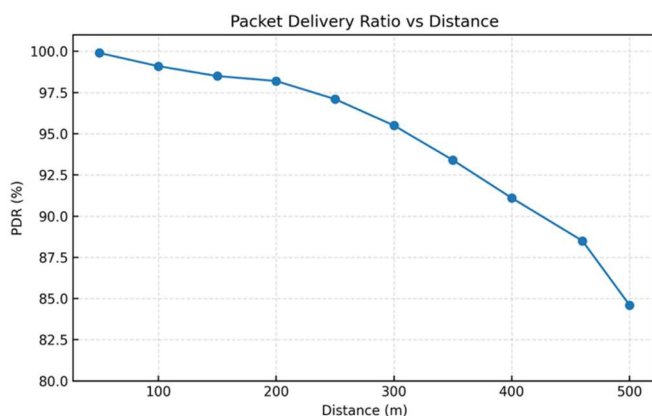


Figure 4. Packet Delivery Ratio with Distance

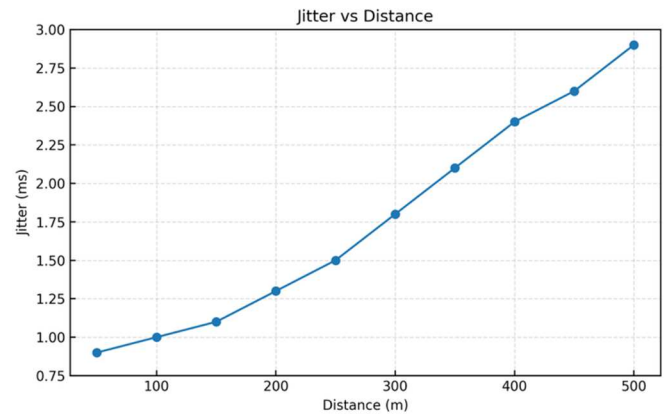


Figure 5. Jitter with Distance

Fig. 4 shows that PDR drops from 99% to around 85% with increasing distance, meaning data integrity significantly deteriorates with distance. Fig. 5 shows that jitter rises from about 1 ms at short distances to nearly 3 ms at long distances, indicating that latency not only increases but also becomes more unstable. This is particularly detrimental to applications like real-time video streaming. To further compare the performance differences at different distances, Table I summarizes multiple metrics for short distances (≤ 150 m) and long distances (≥ 450 m).

TABLE I. Analysis of Performance Comparison

Metric	Short Distance (≤ 150 m)	Long Distance (≥ 450 m)
Average Latency (ms)	14.6	45.5
Average Throughput (Mbps)	16.2	3.7
Packet Delivery Ratio (%)	99.2	86.5
Average Jitter (ms)	1.0	2.75
Energy per Bit (nJ)	137	580

As shown in Table I, short distances offer significant advantages in latency, throughput, packet delivery ratio, and energy consumption. For instance, short-distance latency is only about 14.6 ms, throughput reaches 16.2 Mbps, PDR remains at 99.2%, and energy per bit is only 137 nJ; in contrast, long-distance latency increases to 45.5 ms, throughput drops to 3.7 Mbps, PDR is only 86.5%, and energy consumption is as high as 580 nJ/bit. These results highlight that UAVs will face dual challenges in communication and energy efficiency during long-distance missions. In UAV systems, energy efficiency is often the key factor limiting mission endurance. Communication consumes transmission power, and when throughput decreases, the energy cost per bit of data increases.

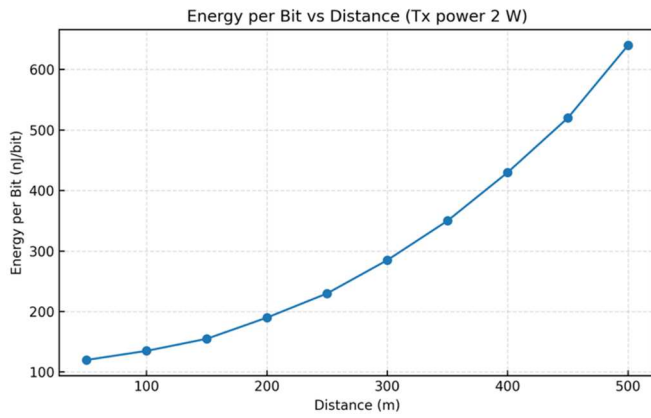


Figure 6. Energy per Bit with Distance

Fig. 6 shows that energy per bit significantly rises with distance: it is only about 120–160 nJ/bit at short distances, while it exceeds 600 nJ/bit at 500 m. This result means that the UAV's battery consumption rate accelerates during long-distance transmission, directly affecting mission endurance time. Therefore, how to reduce energy consumption while ensuring data integrity is a crucial issue in UAV-ISAC system design. Spectrum efficiency is another important indicator for 5G/ISAC systems, which is highly related to the resource allocation strategy. To further analyze the impact of bandwidth allocation on communication performance, a bandwidth sensitivity analysis is conducted.

Fig. 7 illustrates that across all evaluated bandwidth configurations (1.4–20 MHz), higher bandwidth consistently leads to lower latency and higher throughput at all distances, while the distance-dependent degradation trend remains unchanged.

Fig. 7 and Table II show that at 100 m, increasing the bandwidth from 3 MHz to 10 MHz improves throughput from approximately 27 Mbps to 58 Mbps, while reducing latency from about 14 ms to 12 ms. At 400 m, throughput increases from around 9 Mbps to 22 Mbps, and latency is reduced by approximately 17%. Although the distance-dependent degradation still exists, increasing bandwidth effectively alleviates performance degradation. These results confirm that resource allocation strategies play a significant role in UAV-ISAC system performance, which is consistent with the literature's discussion on the spectrum efficiency trade-off.

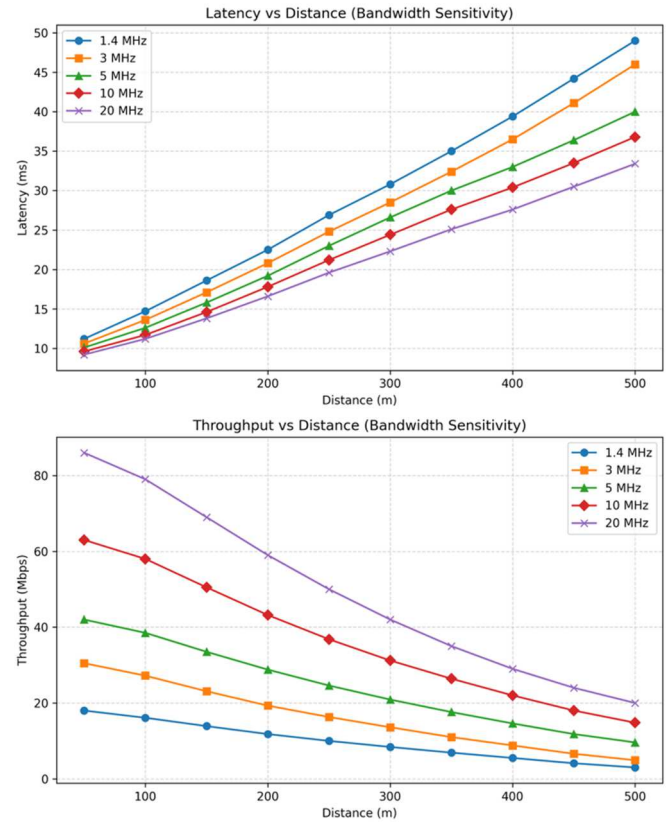


Figure 7. Latency and Throughput Comparison under Different Bandwidth Configurations

TABLE II. Performance Comparison of UAV-ISAC System Under Different Bandwidth Configurations (3 MHz and 10 MHz)

Distance (m)	Latency (ms, 3MHz)	Latency (ms, 10MHz)	Throughput (Mbps, 3MHz)	Throughput (Mbps, 10MHz)
100	13.6	11.7	27.2	58.0
400	36.5	30.4	8.8	22.0

V. CONCLUSION

This study successfully validated a UAV-ISAC simulation architecture using DroneKit and NS-3, offering a robust tool for analyzing next-generation environmental monitoring systems. By establishing this joint framework, we quantified the critical performance limits imposed by dynamic operational distance and resource allocation. The simulation results demonstrate that the distance increase from 50m to 500m causes a significant rise in latency, accompanied by sharp decreases in throughput and data integrity; packet jitter also substantially increases. Critically, we demonstrated that long-distance transmission severely degrades communication energy efficiency, significantly reducing the UAV's mission endurance—an essential, practical constraint for aerial platforms. While increasing bandwidth proves to be an effective compensatory strategy, it cannot entirely overcome the performance bottleneck caused by path loss and distance. These findings are not merely confirmations of path loss theory; they provide

quantitative reference points on communication reliability and energy consumption. The verification of this architecture confirms the feasibility of UAV-ISAC and identifies distance, energy consumption, and bandwidth as the critical factors influencing its real-world deployment. This study's primary contribution lies in offering essential, quantitative reference points for future UAV-ISAC system design and optimization strategies, especially regarding trajectory planning and resource allocation in dynamic aerial scenarios.

VI. FUTURE WORK

Although this study has developed the UAV-ISAC simulation architecture and completed preliminary verification, several promising directions remain for further exploration. In the future, we will further consider multi-UAV cooperation scenarios to analyze monitoring efficiency and communication stability under different altitudes and trajectories. Simultaneously, we will design various spectrum and power resource allocation strategies to balance sensing accuracy and communication performance.

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